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ABSTRACT

This study has analyzed the force acting on the control valve and built the mathematical model of control valve, which can analyze the steady state and dynamic behavior of control valve. Using the mathematical model, this paper has explained the cause of hunting found in experiment.

NOMENCLATURE

A: flow area, area of force
F: Force
G: mass flux
M: mass
R: radius
U: inner energy
x: radius of force on cone valve
α: flow coefficient
ρ : density
c: velocity, constant
h: enthalpy
k: elastic coefficient, flow coefficient
P: pressure
t: temperature
v: specific volume
y: displacement of valve rod or ball valve
ε : expansion coefficient

Subscripts:

b : ball valve
d : discharge
s : spring
c: crankcase
e: evacuated bellows
w: valve wall

INTRODUCTION

There are two types of automobile air conditioning system using variable displacement compressor. One is automobile air conditioning system with orifice tube and variable displacement compressor. The other is thermal expansion valve and variable displacement compressor. Because orifice tube cannot regulate the circulating mass of refrigerant and cannot use the liquid refrigerant in the gas-liquid separator, the refrigerator efficiency is low. The refrigerating system with thermal expansion valve and variable displacement compressor can conquer those disadvantages. But the variable displacement compressor with thermal expansion valve in automobile air conditioning system have been found hunting during the actual using and experiment. In order to solve the problem, it is urgent to study the behavior of the control valve in variable displacement compressor, which is the regulating component of variable displacement compressor.

This paper takes the V-5 Variable Displacement Wobble Plate Compressor (Figure 1) for example. V-5 compressor control valve, which is installed in the rear head of the compressor, maintains the evaporator just slightly above freezing which maximizes the amount of available cooling and dehumidification. The function of control valve in the V-5 compressor is to regulate the compressor crankcase pressure that combines with discharge pressure and suction pressure creating a net force on each of the five pistons and in turn changing the displacement of V-5 compressor. In order to compute the crankcase pressure, we must build a mathematical model of control valve.

MATHEMATICAL MODEL OF CONTROL VALVE

A sectional view of V-5 compressor and control valve is shown in Figure.1 and Figure.2. The control valve (Figure 2), which connects the discharge cavity, crankcase and suction cavity utilizes an evacuated bellows to sense suction pressure. When the evaporator load is low, the suction pressure is below the preset control point of control valve and the evacuated bellows is extended. Then the ball valve is open and the flow area of cone valve decreases. As there is a bleed from discharge cavity to crankcase and also a bleed from crankcase to suction cavity, the crankcase pressure is built, which combines with discharge pressure and suction pressure creating a net force on each of the five pistons and in turn makes a reducing displacement to meet the demand of evaporator load. When the evaporator load is high and the suction pressure increases, the evacuated bellows is compressed, the flow area of ball valve is reduced and the flow area of cone valve is increased. Then with the reducing of the crankcase pressure, the displacement of the compressor is increased. Under the operation of the control valve, V-5 compressor changes its displacement according to the evaporator load.

Force Analysis of Control valve

To build the mathematical model, we must analyse the force acting on the control valve. Figure 3 shows the force on the valve rod and Figure 4 shows the force on the ball. From Figure 3, the force balance equation of the valve rod can be obtained:

$$F_{ss} + F_{Ps} = F_{Pc2} + F_{cs} + M_r \cdot g + F_{Pc1} + F_b \qquad (1)$$

From figure 4, the force balance equation of the ball can be obtained:

$$F_{Pc1} + F_{wb} + F_b = F_{Pd} + F_{ds} + M_b \cdot g \qquad (2)$$

Bring equation (2) into equation (1), the force balance equation of the valve rod is:

$$\begin{aligned}&(K_{ds} + K_{cs} + K_{bs}) \cdot y + \pi \cdot (P_d - P_c) \cdot (R \cdot \sin\alpha)^2 + P_c \cdot \pi x_c^2 + (P_s + 10^5) \cdot A_e - P_s \cdot \pi \cdot x_c^2 \\ &= F_{bs0} - F_{ds0} - M_b \cdot g - M_r \cdot g - F_{cs0} = C\end{aligned} \qquad (3)$$

Equation (3) is proper when cone valve and ball valve are all opening. The right side of the equation is constant. When the ball valve is closed, the force balance equation of the valve rod is:

$$\begin{aligned}&-F_w + \pi \cdot (P_d - P_c) \cdot (R \cdot \sin\alpha)^2 + P_c \cdot \pi \cdot x_c^2 + (P_s + 10^5) \cdot A_e - P_s \cdot \pi \cdot x_c^2 \\ &= F_{ss0} - M_r \cdot g - M_b \cdot g - F_{cs0} - F_{ds0} = C\end{aligned} \qquad (4)$$

When the ball valve is closed and the rod is separated from the ball, the force balance equation of the valve rod is:

$$(K_{ss} + K_{cs}) \cdot y + P_c \cdot \pi \cdot x_c^2 + (P_s + 10^5) \cdot A_e - P_s \cdot \pi \cdot x_c^2 = F_{ss0} - M_r \cdot g - F_{cs0} \qquad (5)$$

When ball valve is full open and the cone valve is full closed, the equation is:

$$\begin{aligned}&-F_{wb} + (K_{ds} + K_{cs} + K_{bs}) \cdot y_{\max} + \pi \cdot (P_d - P_c) \cdot (R \cdot \sin\alpha)^2 + P_c \cdot \pi x_c^2 + \\ &(P_s + 10^5) \cdot A_e - P_s \cdot \pi \cdot x_c^2 = F_{bs0} - F_{ds0} - M_b \cdot g - M_r \cdot g - F_{cs0} = C\end{aligned} \qquad (6)$$

Considering the inertial force of the ball and rod, the force equation of the valve rod is:

$$\begin{aligned}&(K_{ds} + K_{cs} + K_{bs}) \cdot y + \pi \cdot (P_d(t) - P_c(t)) \cdot (R \cdot \sin\alpha)^2 + P_c(t) \cdot \pi \cdot x_c^2 + (M_r + M_b) \cdot \frac{d^2 y}{dt^2} \\ &+ P_s(t) \cdot A_e - P_s(t) \cdot \pi \cdot x_c^2 = F_{bs} - M_r \cdot g - M_b \cdot g - F_{ds0} - F_{cs0}\end{aligned} \qquad (7)$$

Because the accelerated speed and the mass of rod and ball is very small comparing with others items, the inertial force can be neglected and the equation (7) is equal to equation (3).

When the evaporator load is low and the suction pressure P_s is blow the preset control point, the ball valve is open and the preset control point is equal to P_s. From equation (4), the preset control point can be obtained:

$$P_{s0} = \frac{(F_{bs0} - M_b \cdot g - M_r \cdot g - F_{cs0} - F_{ds0}) - \pi \cdot P_d \cdot (R \cdot \sin\alpha)^2}{A_e - \pi \cdot (R \cdot \sin\alpha)^2} \qquad (8)$$

Table 1 Comparison of the preset control point

Pressure P_d（bar）	Calculation （bar）	Experiment Data（bar）	Data of a Company（Bar）
7.1	2.032	1.958	2.04
13.5	1.626	1.626	1.68

Figure 5 shows relation between discharge pressure and preset control point. Preset control point is in inverse linear proportion with discharge pressure. Table 1 is the comparison between experimental data, calculation and the data from a company.

The Mathematical Model of Control Valve

The purpose of the control valve model is to determine P_c when P_d and P_s vary. The control valve model includes the following equations:

(1) The force equation of valve rod.

(2) The mass flux equation of the ball valve: $G_d = \alpha_d \cdot \varepsilon_d \cdot A_d \cdot \sqrt{2\rho_d (P_d - P_c)}$ (9)

The mass flux equation of the cone valve: $G_c = \alpha_c \cdot \varepsilon_c \cdot A_c \cdot \sqrt{2\rho_c (P_c - P_s)}$ (10)

The flow coefficient α_c and α_d are obtained form experiment.

(3) The state equation of refrigerant: $P = f(t,v) \quad h = f(t,v)$ (12)

(4) The control volume equation of crankcase: $\frac{dM_c}{dt} = G_d - G_c$ (13)

$$\frac{d(M_c \cdot U_c)}{dt} = G_d \cdot h_d + \frac{c_d^2}{2} \cdot G_d - G_c \cdot h_c + Q_c \quad (14)$$

In the energy equation, because of the high speed of refrigerant from the discharge cavity to the crankcase, it takes account the kinetic energy of refrigerant. Using the mathematical model of control valve, we can calculate the steady-state and dynamic behavior of control valve.

EXPERIMENT PROGRAM OF CONTROL VALVE

In order to verify the mathematical model of control valve, a set of experiment device and experiment program are designed. The schematic diagram of experimental program is shown on Figure 6. The displacement of the ball valve can be measured by the displacement sensor and the pressure P_d, P_c, P_s can be measured by pressure sensor. All the data are collected by HP 34970A data acquisition, which translates the experiment data into the computer. Nitrogen has been used as test medium in our experiments. There are three cavities (discharge cavity, suction cavity and crankcase cavity) to simulate the cavity in V-5 compressor. Using the flow meter, the flow coefficient can be gotten from experiment, which is the function of Reynolds number. In order to keep P_s or P_d constant, two constant pressure valves are used. Opening and closing different valves near the constant pressure valve, two-way gas supply and one-way gas supply can be used in experiment.

STEADY-STATE BEHAVIOR OF CONTROL VALVE

Using the mathematical model of control valve, the steady-state simulation of the control valve can be done. One-way gas supply experiment is used to verify the validity of the simulation. When Pressure P_d is constant (for example 6.5 bar), the relations between y and P_c, P_s, G, are shown in Figures 7-9 (the max displacement of the control valve in experiment and simulation is 0.4mm). Figures 10-12 are the relations when discharge pressure is 13.3 bar. The simulation and experiment all use Nitrogen as substitute for R134a. In experiment, Nitrogen in high pressure after the constant pressure valve goes into the discharge cavity of the control valve firstly and goes out from the evacuated valve. The displacement of the control valve varies with different opening of the evacuated valve. In experiment the control valve cannot maintain stable without hunting while y, the opening of the ball valve increases high enough. The cause of the hunting will be discussed later. In Figures 7and10, the pressure P_s decreases as the displacement of the control valve raises. The suction pressure P_s is the main factor of the displacement of the control valve. The pressure P_c changes a little in beginning and increases largely while the ball vale opens widely (Figures 8,11). The mass flux increases as the control valve opens and decreases before full opening in simulation (Figures 9,12). From simulation we can see the mass flux gets its top point when the ball valve opens about 70%. Comparing the simulation and experiment, the simulation agrees with the experiment data properly before the hunting area. Figure 13 compares the calculated P_c with the experiment P_c while the control valve is working in the refrigeration system (R134a). In Figure 13, about sixty points of steady state have been compared.

DYNAMIC SIMULATION OF THE CONTROL VALVE

Figures 14-15 (the maximum displacement of the control valve in simulation and experiment is 0.27mm) are the comparison of the simulation and experiment while discharge pressure P_d changes. In experiment we make the control point of constant pressure valve drop down suddenly and record the changes of P_d, P_c, P_s and Y. After that the mathematical model of control valve is used to simulate the changes of P_c and Y. In simulation P_d and P_s are regarded as given data. The simulation results agree with the experiment data, which approve the feasibility of the mathematical model of the control valve. Because in experiment, it is hard to make a step change of P_d while P_s maintains constant, simulation is used to anticipate the dynamic behavior of control valve while P_d or P_s makes a step change when the other one keeps constant. Figures 16-23 are simulation when P_d or P_s has a step change. In Figures 18 and 19, when P_d steps up, the displacement of ball valve and cone valve, the mass flux of ball valve reduces suddenly and mass flux of cone valve also has step changes with P_d pressure at beginning because of sudden change of force on the valve rod and sudden change of flux areas of ball valve and cone valve. After first abrupt change, the P_c pressure decreases and pushes the valve rod up. While the displacement of ball valve increases and the displacement of cone valve decreases with the decreasing of P_c pressure, the mass flux of ball valve increases and the mass flux of cone valve decreases. In the end, G_c and G_d are equal, P_c pressure, y, displacement of ball valve are stable. The other figures show similar changes. All figures show that the transition time is very short (around one second) and the displacement of y has overshoot.

HUNTING OF CONTROL VALVE

In experiments of steady-state experiment, one-way gas supply method is used. As evacuated valve opens, P_s decreases and the displacement of ball valve, y, increases. When y reaches certain point while P_d maintains constant, the valve rod begins hunting, even if the evacuated valve opens a little more. Figures 24,25 are the records of experiments of hunting. In Figure 24, the ball valve only full opens and full closes once and then remains stable again. After that, open the evacuated valve larger to make P_s lower, the hunting of the valve rod appears (Figure 25). Besides hunting, there is another possibility: if P_d is not high enough, the ball valve will has just a sudden change to full open and maintains stable when evacuated valve open larger because under such condition P_s and P_c pressure cannot increase high enough to close the ball valve. To find the cause of hunting, a mathematical model is built on the base of the mathematical model of control valve. One-way gas supply has been simplified to Figure 29. In the mathematical model, we assume there is no chamber after the cone valve and G_c=G_s.

Define $k_c = \dfrac{1}{2\alpha_c^2 \cdot \varepsilon_c^2 \cdot A_c^2}$, the mass flux equation of the cone valve is changed to: $\dfrac{(P_c - P_s)\cdot P_c}{RT} = k_c \cdot G_c^2$ (15)

The mass flux equation of the evacuated valve: $\dfrac{(P_s - P_0)\cdot P_s}{RT} = K_s \cdot G_s^2, k_s = \dfrac{1}{2\alpha_s^2 \cdot \varepsilon_s^2 \cdot A_s^2}$

Because G_c equals G_s, we can get: $P_s = \dfrac{\sqrt{4k_c \cdot k_s \cdot P_c^2 + (k_c \cdot P_0 - k_s \cdot P_c)^2} - (k_s \cdot P_c - k_c \cdot P_0)}{2k_c}$ (16)

In above equations, the pressures are absolute pressures and P_0 equals to 1 bar. Decreasing the value of k_s is similar to open evacuated valve. After differencing the control volume equation of crankcase, the mathematical model is a set of algebraic equations. We assume P_d equals 8 bar and maintains constant. Under different initial condition of control valve, we make k_s step down 2% and get the following results: Figures 26,27. Before making a step change of k_s while control valve is stable, solve the algebraic equations of mathematical model, the displacement of valve rod y has root less than the maximum value of y. After the step change of k_s (Figure 26 and Figure 27), the evacuated valve opens larger, there is no root of y less than y_{max} while using force Equation 3. So y reaches y_{max} and holds to it while P_c becomes to increase. At this time, the force equation is Equation(6) and F_{wb} >0. P_s pressure becomes to increase from it minimum after its initial step change and F_{wb} becomes to decrease because of the increasing of P_c and Ps. While P_c and P_s reaches the point to push the valve rod down (F_{wb}=0), y is about to decrease, which makes k_c to decreases because A_c is in inverse proportion with k_c. Decreasing of k_c makes P_s increase for P_s is in inverse proportion with k_c. The increasing of P_s makes y to decrease more until cone valve is full open and k_c cannot change any more. At this time, solving the algebraic equations while using force Equation 3, there is no root of y higher than zero and lower than y_{max}, which means force equation 4,5 are used and y has a sudden change (in Figures 26,27, y is under zero which means valve rod is separate from the ball valve). After full close of ball valve, there is no gas supply to P_c. So P_c becomes to decrease while P_s decreases too. With the decreasing of Pc and Ps, the valve rod becomes to move up. As y increases to certain value (the algebraic equations have no root lower than y_{max}), shown in Figure 27, P_c and P_s become to separate and y has a sudden change to y_{max}, valve rod continues hunting. In Figure 26, after y experiences a full open and full close, it becomes stable (the algebraic equations haves root lower than y_{max} and there is no sudden change of y). The periodic time of hunting is up to the volume of crankcase cavity and the P_d. In summary, the cause of hunting is the interaction of P_s and the G_c. If P_s and P_d are independent, there is no hunting happened. Two-way gas supply has vitrified it (In figure 28, the control valve can full open without any hunting while P_s has no interaction with G_c.)

CONCLUSIONS

The mathematical model of control valve is built. Using this mathematical model, the steady state and dynamic behaviour can be analysed. The critical parameter P_c pressure for dynamic analyse of V-5 compressor can also be calculated by the mathematical model. In the end, we analysed the hunting of control valve appeared in the experiments and found the cause of it.

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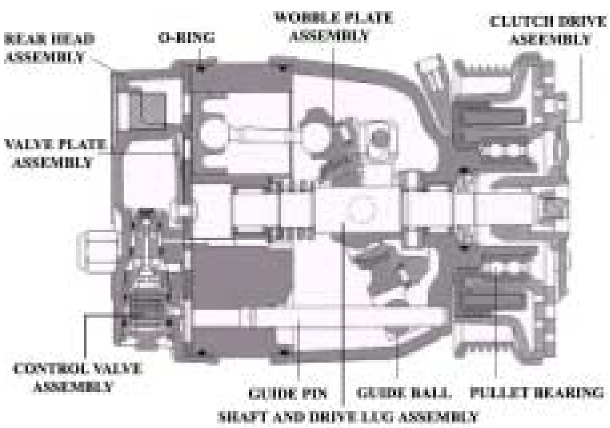


Figure 1 V-5 Variable Displacement compressor

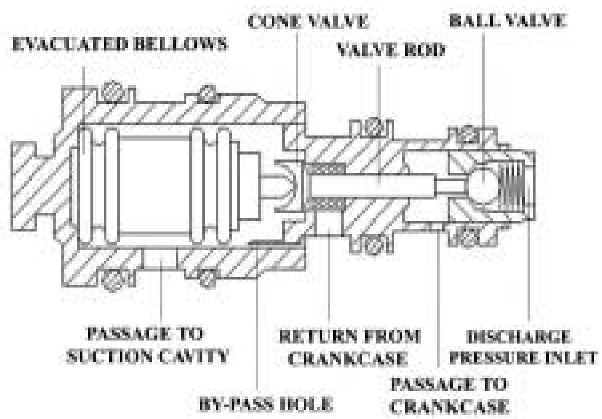


Figure 2 Control Valve

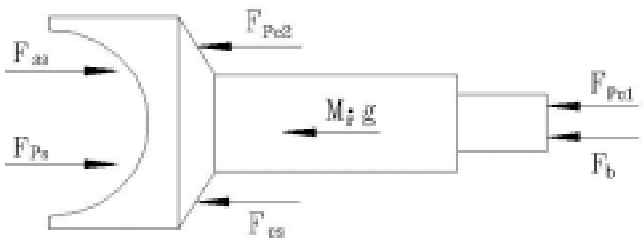
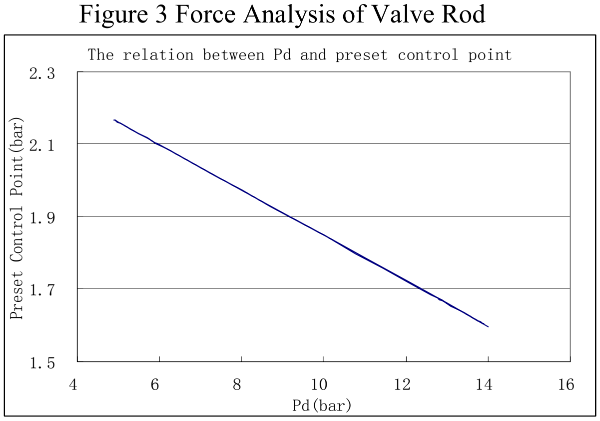


Figure 3 Force Analysis of Valve Rod

Figure 4 Force Analysis of Ball Valve



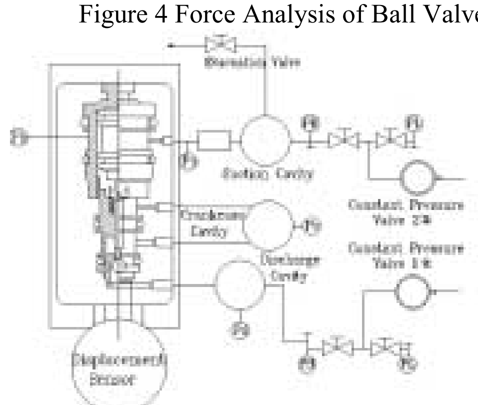
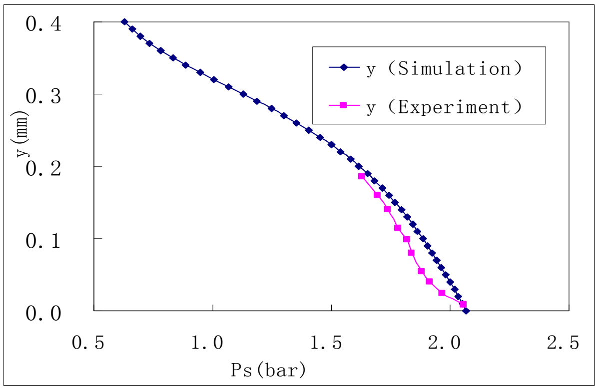


Figure 5 The Relation Between Pd and Preset Control Point

Figure 6 The Schematic Diagram of Experimental Program



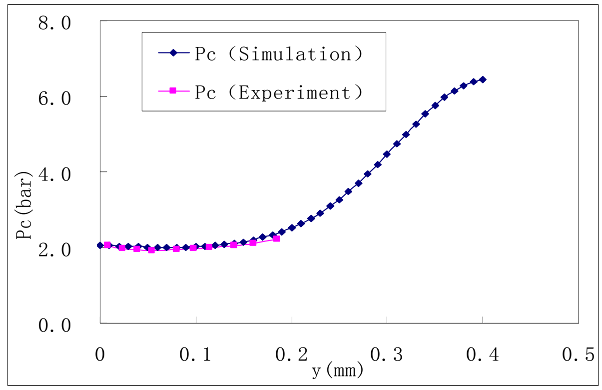
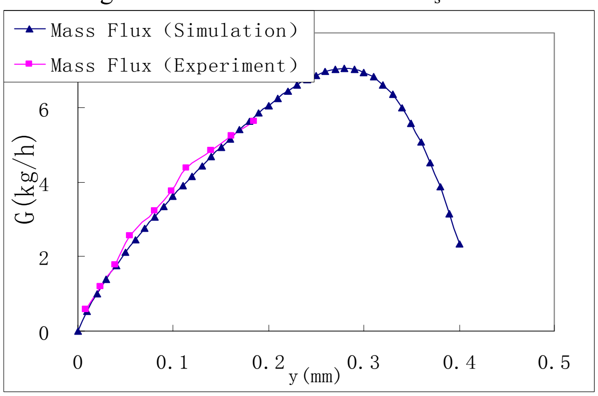


Figure 7 The Relation Between P_s and Y

Figure 8 The Relation Between P_c and Y



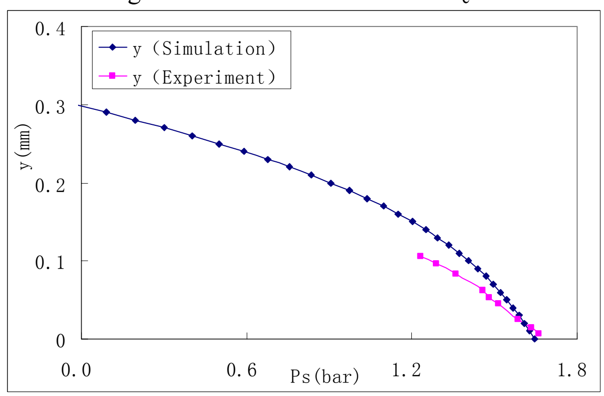
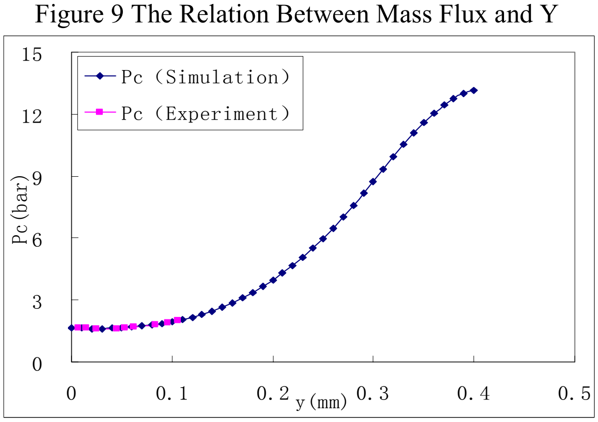


Figure 9 The Relation Between Mass Flux and Y

Figure 10 The Relation Between P_s and Y



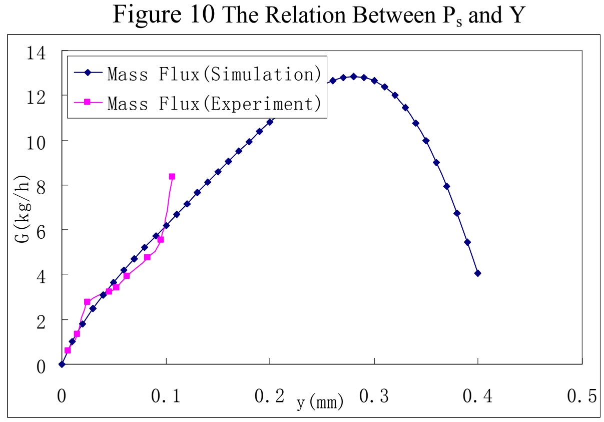
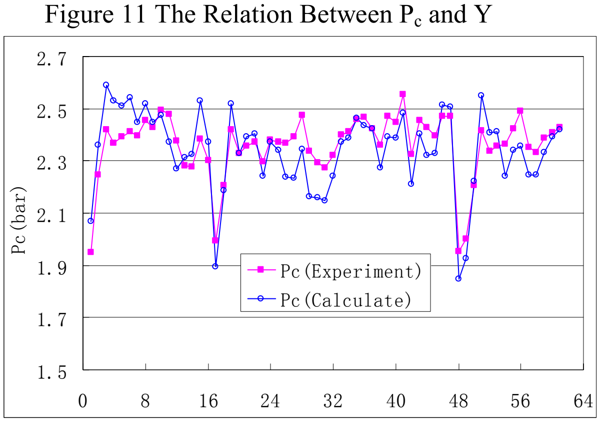


Figure 11 The Relation Between P_c and Y

Figure 12 The Relation Between Mass Flux and Y



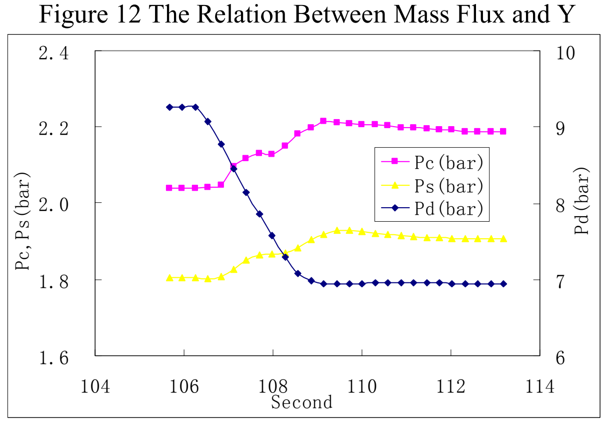


Figure 13 Compare Pc in Real Operation

Figure 14 Experiment of P_d changing

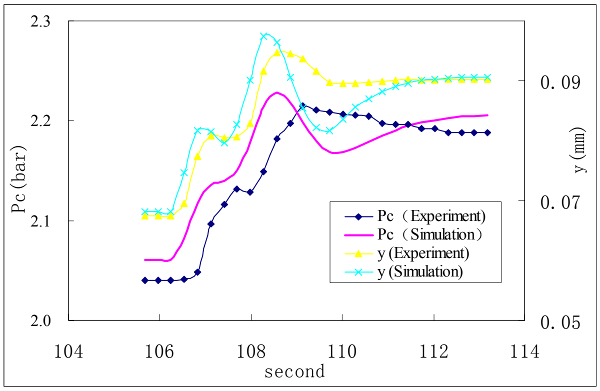


Figure 15 Comparing experiment and simulation of P_c, y

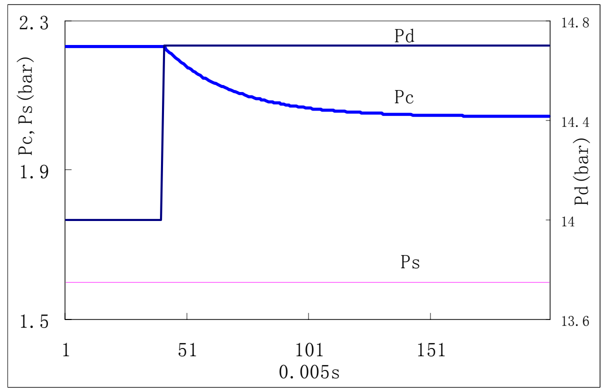


Figure 16 P_d Step Up 5%

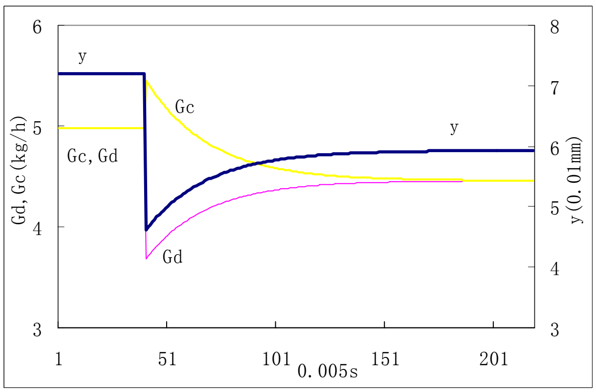


Figure 17 P_d Step Up 5%

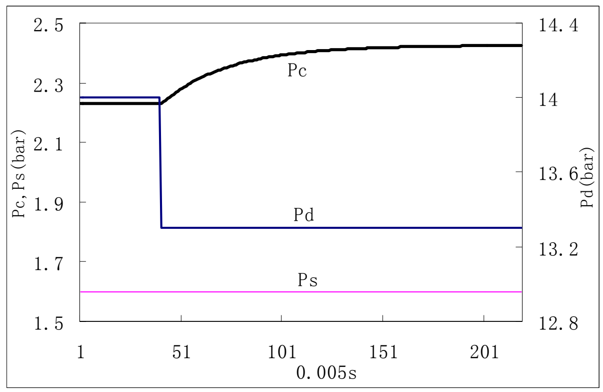


Figure 18 P_d Step Down 5%

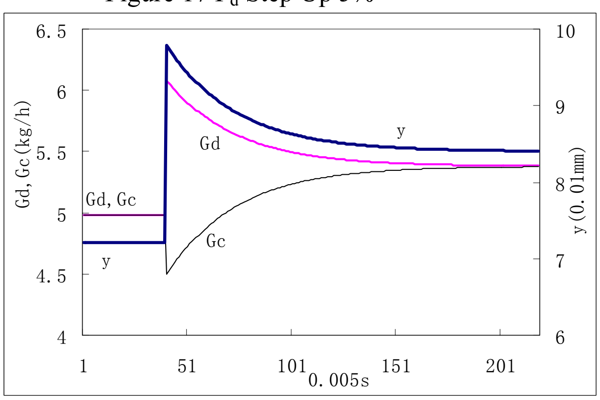


Figure 19 P_d Step Down 5%

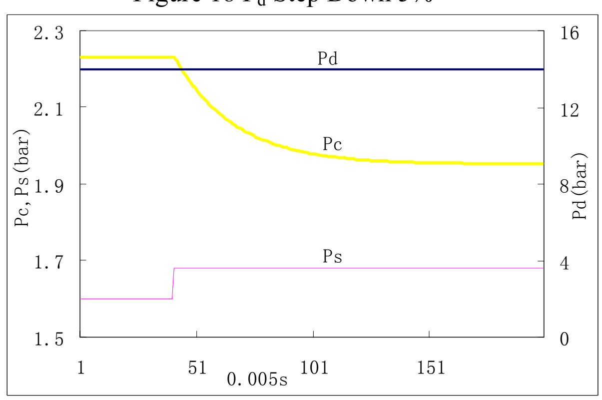


Figure 20 P_s Step Up 5%

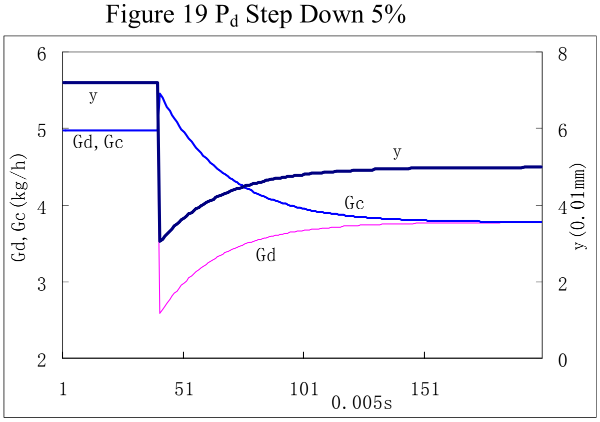


Figure 21 P_s Step Up 5%

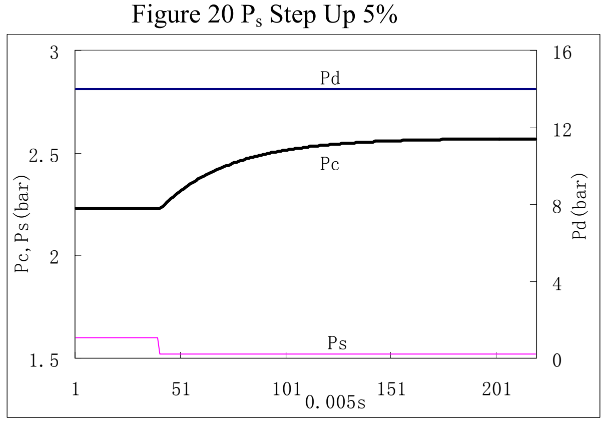


Figure 22 P_s Step Down 5%

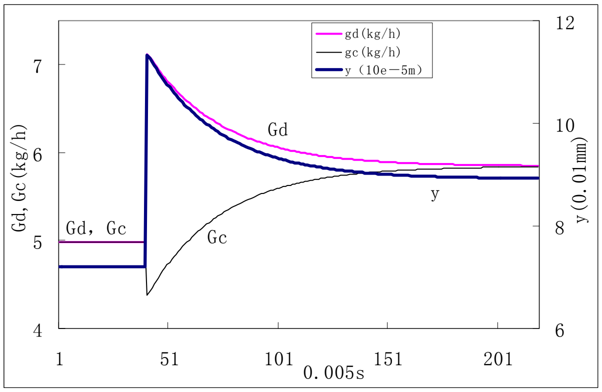


Figure 23 P_s Step Down 5%

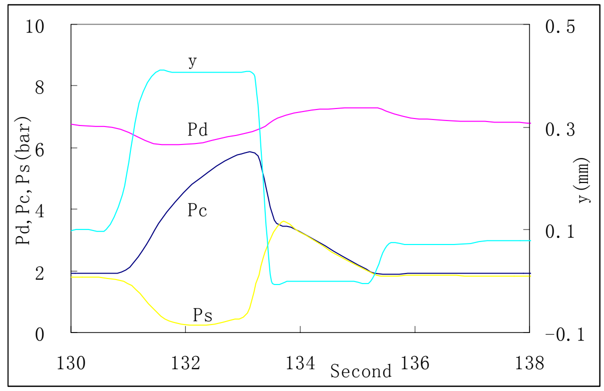


Figure 24 Hunting of Control Valve in Experiment

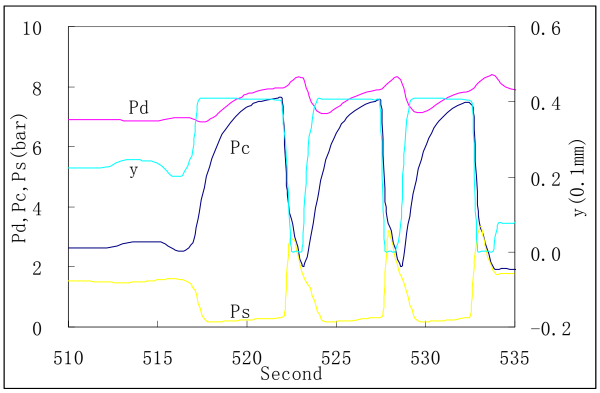


Figure 25 Hunting of Control Valve in Experiment

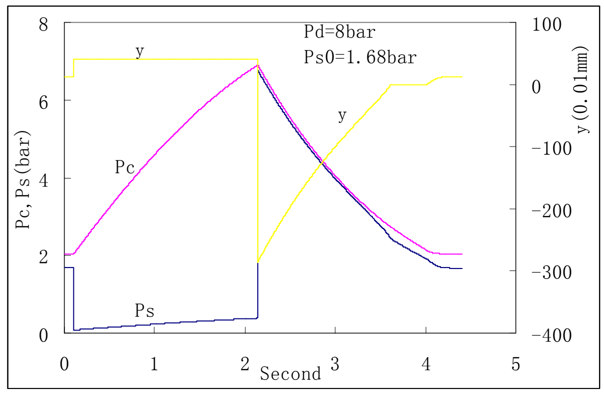


Figure 26 Hunting of Control Valve in Simulation

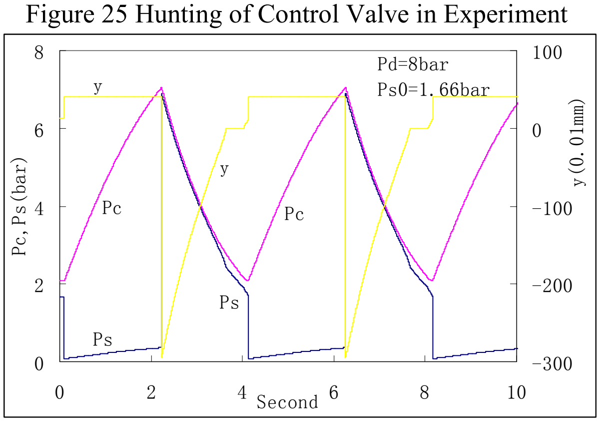


Figure 27 Hunting of Control Valve in Simulation

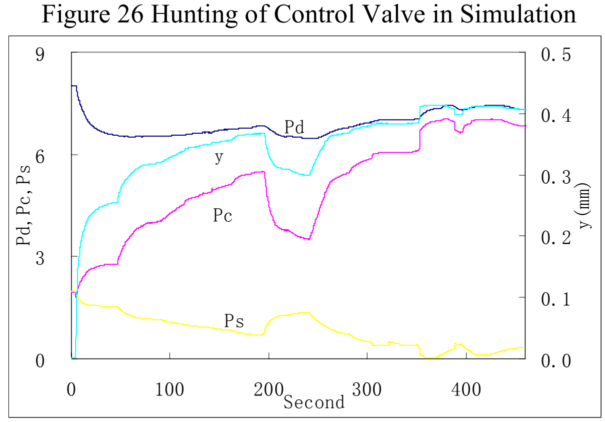


Figure 28 Two-way Gas Supply

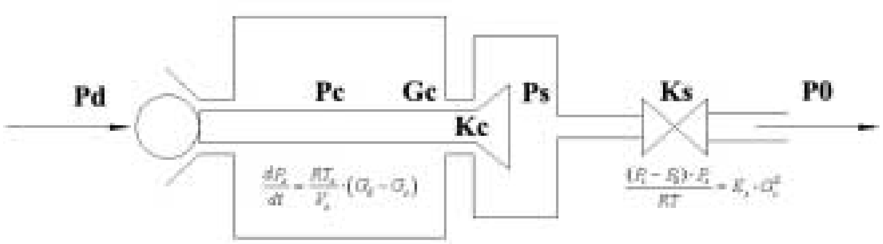


Figure 29 One-way Gas Supply